Teaching Green Concrete

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ABSTRACT

Concrete is a construction material used intensively all around the world. The principal components of concrete are Portland cement, water, gravel, sand and chemical admixtures. The production of Portland cement requires significant amounts of energy and is an important contributor to the global warming. This paper presents a teaching experience using fly ash type F and lightweight aggregates to reduce the consumption of Portland cement that result in Green Concretes. The students participate in the planning, mixing, and testing of the concrete to obtain important engineering properties, and in the construction and testing of a postensioned T-beam, a postensioned segmental beam, and two reinforced concrete T-beams. The Green Concrete projects motivate the student participation, the course outcomes are fully accomplished, and the students gain experience using environmentally friendly materials.

Keywords: Green concrete, environmentally friendly concrete, lightweight concrete, fly ash.

1. INTRODUCTION

Concrete is a strong, durable and economic construction material with different engineering applications. The principal components of concrete are coarse and fine aggregates, water, Portland cement and other bindings, and chemical additives, which, with a proper mix design and construction procedure, produce the concrete with the required engineering properties. In general, concrete is environmentally friendly because its components are found locally, it is highly recyclable, and old and abandoned concrete structures degrade under the effect of organisms. However, the elaboration of the Portland cement, which is a basic component of concrete, requires large amount of energy and release large quantities of carbon dioxide (CO_2) to the atmosphere. Any reduction of Portland cement is beneficial and we can achieve this goal by replacing the Portland cement with fly ash, or reducing the volume of concrete required for the project; both methods lead to the material called Green Concrete.

In construction practice, the engineers write the technical specifications indicating the materials permitted for the project; for this reason, the students must to know the properties of the Green Concrete. The Structural Analysis and Design Program of the University of Houston Downtown has the course Modern Concrete Technology to study the concrete as a material, and other courses for design of concrete structures, like Reinforced Concrete and Senior Concrete Design. In these courses, the students gain experience with the mix design, manufacturing, use of modern admixtures, testing, structural design, and with the technical report of their findings.

In the course Modern Concrete Technology, the students develop a project to understand the concrete properties consisting in the design and test of different mixes (Tito et al, 2005). The Senior Concrete Design has projects involving the structural analysis and the knowledge of the materials. The hands-on experience is the principal methodology to teach these courses. During the last years, these courses incorporated the study and use of Green Concretes obtained with fly ash or with lightweight aggregate, which comply with the objective of the courses and with social responsibilities of engineering. The strength, workability, consistency, and economy of a Green Concrete may be different from normal concretes being necessary a direct experience to be confident with its use.

2. MIX DESIGN

The first classes of the course Modern Concrete Technology focus on learning about the use of concrete, the engineering properties and the tests required to characterize the materials and the resultant concrete. The students work in groups of four or five individuals along the semester. On past semesters, former students helped as voluntary teacher assistant, making valuable contributions to the projects.

The first tests are to know the aggregates obtaining the grain size distribution, specific gravity, bulk density, and water content. The Portland cement is type I and bought in a local store the same day of the test and always the same brand name. The typical chemical admixture is a plasticizer, which is useful to increase the workability principally when the water-cement ratio is low.

The spreadsheet called "ACI-Method" helps for the mix design; the author developed the program based on the procedure described by the American Concrete Institute (ACI 1991, ACI 1998). The spreadsheet is versatile permitting the use of other materials. The spreadsheet also is useful to register the test results. Figure 1 shows an example of a mix design using the spreadsheet.

The concretes used for the research contain materials donated by local industries. The fly ash is from Headwater Resources, the lightweight aggregates are from Texas Industries, and the normal weight aggregates are from Flexicore of Texas. The size of the sampler cylinders are 3-in diameter and 6-in height, which provides good results for aggregates with maximum size of 3/8". Each group makes an average of 20 cylinders per mix.

The mixing start after the semester project is well defined. The compression and tension tests of the samples are every 7 days along 4 to 6 weeks.

3. PROJECTS WITH FLY ASH TYPE F

The fly ash type F is a byproduct from the coal industry, which must be disposed carefully to avoid contamination. Its use as Portland cement replacement is an advantage from different point of views, saving the cost of disposal, improving some properties of the concrete, and reducing costs. The Environmental Protection Agency (EPA) considers that the encapsulation of fly ash inside the concrete does not represent risks of contamination such as improper disposal in landfills (EPA 2010).

The students of Structural Analysis and Design made different projects using fly ash type F, and some of them published in professional conferences. All these projects used the fly ash provided by Headwater Resources and normal weight aggregates of 3/8-in maximum size provided by Flexicore of Texas. The experiments are done using a control group without replacement of Portland cement (100%C-0%FA) and other groups replacing Portland cement by fly ash type F in different proportions, varying from 25% to 70% of replacement. The 25% replacement of Portland cement by fly ash is a quite common practice, and more than 50% of replacements are concretes with high fly ash content. The mixes had different ratios of water/cementitious (w/c) varying from 0.22 to 0.60, providing a large range of compression strengths, from 3 ksi to 12 ksi. Portland cement and the fly ash type F are the cementitious materials.

These researches show that replacing the Portland cement by fly ash type F permit the elaboration of concretes of structural grade. However, some properties are different and need further study, such as the initial compression strength, the tension strength, the workability, the temperature release during the hydration reaction, and the surface finishing.

The fly ash type F reacts with the product of the reaction of the Portland cement and water, thereby resulting in concretes that have lower initial strengths respect to the control group. Figure 2 shows examples of the compression strength (fc) along the first 56 days for different mixes. Figure 3 shows a normalized strength (fc/f'c1) versus time for the different mixes, observing that concretes with fly ash gain strength at faster rate than the control group. The f'c1 is the compression strength obtained at 28 days of the control group, which has 100% Portland cement.

UNIVERSITY OF HOUSTON - DOWNTOWN **HOUSTON, TX**

DESIGN BY: DATE: SUBJECT: LABORATORY OF CONCRETE MIX DESIGN SHEET NO_____OF____

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G:\UHDclasses\Modern Concrete Technology\ModernconcTech-Fall2011\[ACI-Method-v2012-Lightest.xls Program: ACI-Method-v2009 By: Jorge Tito, PhD, PE

CONCRETE MIX DESIGN

Slump	4	inches.	The slump is a measure of the workability.		water density, γ_w =	62.4 pcf
Maximum Size of Gravel	3/8	inches.	LW Agg: Use 3/8, 1/2, 3/4 inches		RECOMM: For fc>=5 ksi, use MS of gravel <= 3/4 or 1	
Air Entrained Additives	NO		Air entrained additives are used to improve the concrete resistance to extreme cold wheather			
28 days strength, fc	5	ksi.	The range tabulated in this program is from 3 to 14 ksi. Use increments of 0.5 ksi.			
spg gravel	1.56		spg: Specific gravity, from Laboratory Test		Is Lightweight Gravel?	YES
spg sand	1.88		spg: Specific gravity, from Laboratory Test		Is Lightweight Sand?	YES
Water content	385	lb/cy	From Table 3.4. (B)			
w/c ratio	0.48	-	From Table 3.5	From Interpolation function	0.51	CAUTION! w/c may be changed
Cementitious Material	802	lb/cy	water / (w/c)	Avg spg of cementitious =	3.15	
Cement	100%	=	802 lb/cy	spg of cement	3.15	From specifications
Silica Fume	0%	=	0 lb/cy	spg of Silica Fume	2.20	Assumed
Fly Ash Class F	0%	=	0 lb/cy	spg Fly Ash Type I	2.42	HELP
Sand fineness	3		From Laboratory Test			
Bulk Volume of gravel	0.520	cy/cy	From Table 3.6 (D) - Maximum size and Sand Fineness vs Bulk Volume of Coarse Aggregate			
Variation of the Bulk Volume of Gravel [-10,10]% =			0.0%			
Bulk density of gravel	58	pcf	From Laboratory Test		Weight of gravel:	814 lb/cy
Super-Plasticizer	0.00%		Percentage respect to Cement Weight (Follow the Specifications)			
spg of Super-Plasticizer	1.08		From Technical Specifications or Laboratory Test		Super-Plasticizer:	0.0 lb/cy
Air Volume in percentage	3.00%		Respect to the Total Volume. From Table 3.4 - Non-Air entrained			
Other Additive 2	0.00	lb/cy		spg of Other Additive =	1.00	

WEIGHT OF SAND NEEDED

Water	6.17	ft³/cy	The volume of sand is calculated as the difference between the total volume (1 cy or 27 cf) and the volume of the other materials.
Cementitious Material	4.08	ft³/cy	
Coarse aggregate	8.37	ft³/cy	
Super-Plasticizer	0.000	ft³/cy	
Other Additive 2	0.000	ft³/cy	
Air	0.810	ft³/cy	
Volume of sand	7.57	ft³/cy	Sum = 27 ft³/cy

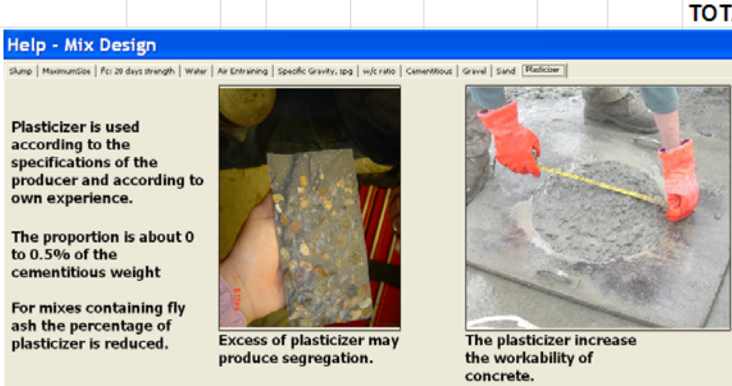
NET INGREDIENTS PER CUBIC YARD (DRY)

Water	385	lb/cy	
Cement	802	lb/cy	
Silica Fume	0	lb/cy	
Fly Ash Class F	0	lb/cy	
Gravel	814	lb/cy	--
Sand	889	lb/cy	--
Super-Plasticizer	0.0	lb/cy	

GROSS WEIGHT / CUBIC YARD (CONSIDERING MOISTURE AND ABSORPTION OF AGGREGATE)

Moisture Content of gravel	20.0%	From Laboratory Test	Moisture Content of sand	20.0%	From Laboratory Test
Absorption of gravel	16.0%	From Laboratory Test	Absorption of sand	16.0%	From Laboratory Test

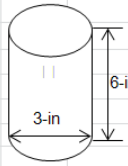
			Price	Commercial Unit			Cost $/lb	$/cy	% of total
Water	317	lb/cy	0.01	$ per		lb	0.01	3.2	3%
Cement	802	lb/cy	173.00	$ per	ton of	2000 lb	0.087	69.4	74%
Fly Ash Class F	0	lb/cy	40.00	$ per	ton of	2000 lb	0.02	0.0	0%
Silica Fume	0	lb/cy	40.00	$ per	ton of	2000 lb	0.02	0.0	0%
Gravel	977	lb/cy	26.00	$ per	ton of	2000 lb	0.013	12.7	14%
Sand	1066	lb/cy	16.00	$ per	ton of	2000 lb	0.008	8.5	9%
Super-Plasticizer	0.0	lb/cy	1600.00	$/55gal-drum	of	458 lb	3.49	0.0	0%
Other Additive 2	0.0	lb/cy	1800.00	$/55gal-drum	of	458 lb	3.93	0.0	0%
						TOTAL COST:		94	$/cy



Help provided for the spreadsheet

Figure 1: Spreadsheet for Mix Design based on ACI Method (continue)

FOR LABORATORY					
MATERIALS FOR LABORATORY		**COST =**	**0.098**	**$/cylinder**	
Diameter =	3	in			
Height =	6	in			
Waste	15%				
Number of Cylinders	20	Cylinders			



Volume =	42.41	in^3	0.0245	ft^3
Volume + Waste =	48.77	in^3	0.0282	ft^3
Total Volume =	975	in^3	0.5645	ft^3 =
			0.0209	cy

LABORATORY TEST

	ORIGINAL MIX DESIGN				ADJUSTMENT OF THE MIX DESIGN DURING THE LABORATORY									
	For 1 cylinder Includes Waste		For N = 20 cylinders		MATERIAL ADDED TO THE MIX DURING THE LABORATORY		NEW GROSS WEIGHT	NEW NET WEIGHT	NEW NET VOL	Net Weight Per CY	Adjusted Weight Per CY	Net Weight Per m^3	Adjusted Weight Per m^3	New Cost
			g	lb			g	g	ft^3	lb/cy	lb/cy	kg / m^3	kg / m^3	$ / cy
Water	150	g	3005	6.63	0	g	3005	3651	0.13	385	317	228	188	3.2
Cement	380	g	7606	16.77	0	g	7606	7606	0.09	802	802	476	476	69.4
Fly Ash Class F	0	g	0	0.00	0	g	0	0	0.00	0	0.0	0	0	0.0
Silica Fume	0	g	0	0.00	0	g	0	0	0.00	0	0.0	0	0	0.0
Gravel	463	g	9267	20.43	0	g	9267	7723	0.17	814	977	483	580	12.7
Sand	506	g	10112	22.29	0	g	10112	8427	0.16	889	1066	527	633	8.5
Super-Plasticizer	0	g	0	0.00	0	g	0	0	0.00	0.0	0.0	0.00	0.00	0.0
Other Additive 2	0	g	0	0.00	0	g	0	0	0.00	0	0.0	0	0	0.0
Air	0	g	0	0.00					0.02					
One Cylinder + Waste =	1500	g	29991		g									
Weight of one Cylinder =	1304	g		66.12	lb			TOTAL VOLUME (ft^3) =	0.565					
Weight of one Cylinder =	2.87	lb						TOTAL WEIGHT (lb) =	3162	w/c ratio =		0.48		
Volume of one Cylinder =	0.0245	ft^3		0.565	ft^3			REAL DENSITY (pcf) =	117					
DENSITY	117	pcf		117	pcf			**New Cost =**	94	$ / cy =		123	$ / m^3	

Figure 1 (continuation): Spreadsheet for Mix Design based on ACI Method.

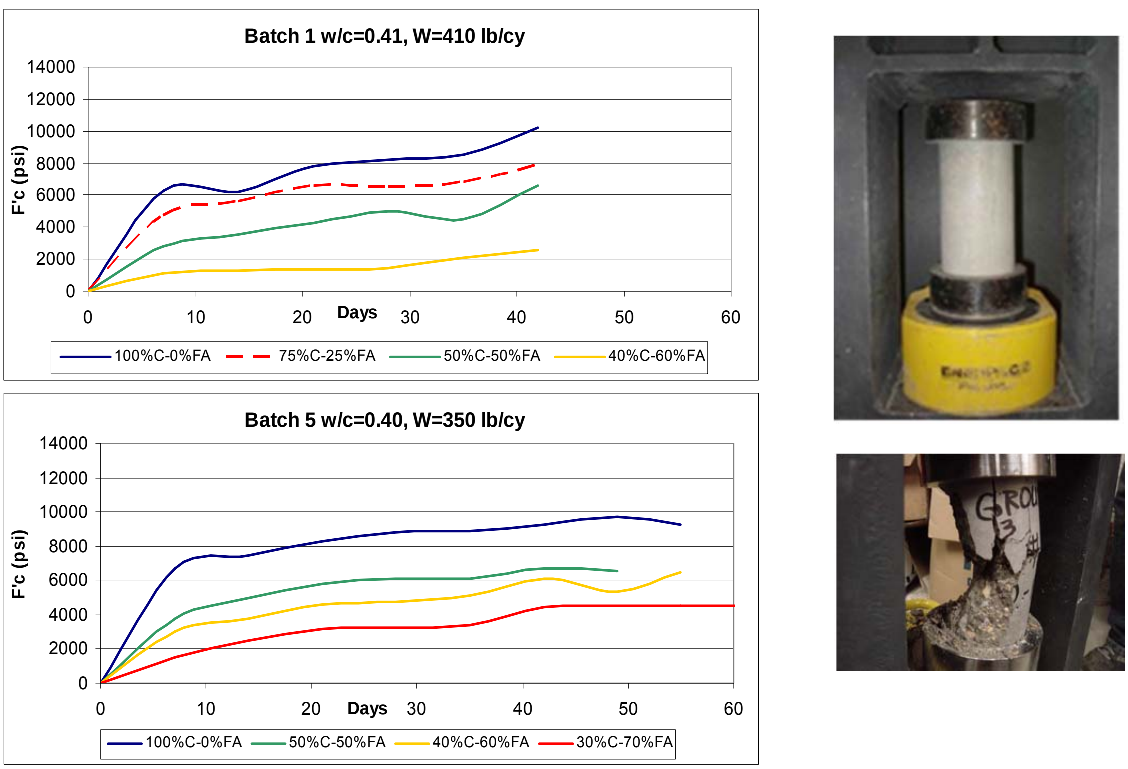
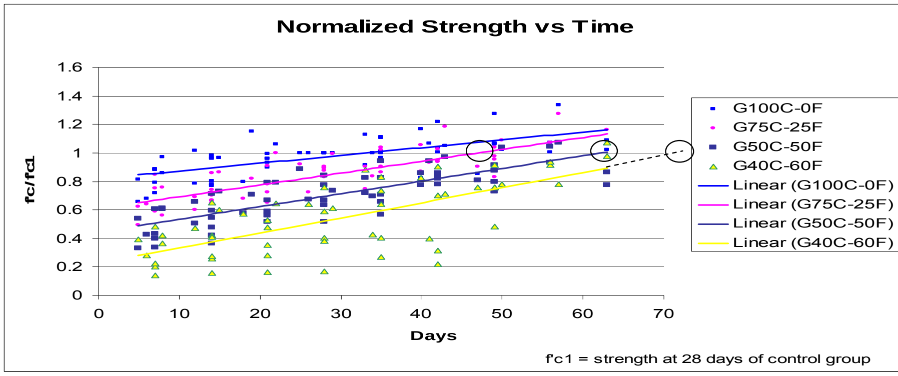


Figure 2: Examples of compressive strengths, fc, vs. time for mixes with fly ash type F.



fc: compression strength.

f'c1: compression strength of control group at 28 days.

Figure 3: Normalized compression strength (fc/f'c1) versus time for each different mixes.

An important conclusion is that concretes with fly ash should have the w/c ratio in the range of 0.30 to 0.40, and the total water content in the mix should be less than 350-lb/cy. Maintaining these ranges, the resulting concretes may reach compression strength of 5000 psi in a reasonable time, which may be between 28 and 56 days depending on the amount of fly ash used. These concretes tend to gain strength after 28 days at a faster rate than the control group. (Aranzales and Tito, 2008).

The Brazilian Test is an economic method to obtain the tensile strength, consisting in the application of a load along the diameter of the cylinder until it splits. The results showed that the ratio of tension and the square root of the compression strength (ft/√(f'c)) tends to reduce when fly ash is used, changing from 6.6 for the control group to 5.6 for concretes with high content of fly ash, as shown in Figure 4.

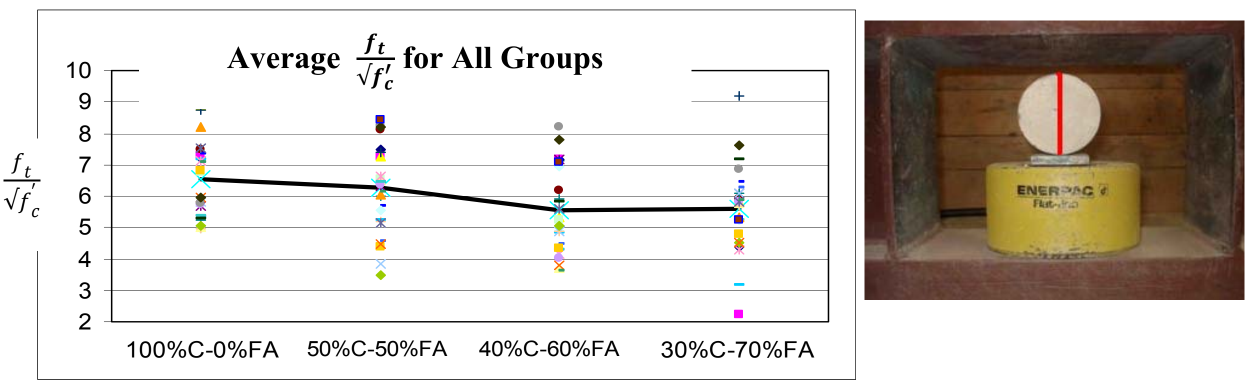


Figure 4: Average of ratio of tension strength (ft) to square root of compression strength (f'c) for all groups.

Figure 5 shows that concrete with fly ash type F have significant reduction of the temperature released during the hydration reaction that is useful to pour massive concrete, or to obtain high strength concrete. Concretes with fly ash have different workability and finishing than the control group. The spherical particles of the fly ash help to improve significantly the workability of the concrete. However, the time for finishing the surface increases because the initial setting is lower. Fly ash concretes have shiny walls after removing the form; however, the surface without form has a dusty aspect (Garza et al, 2006).

Another project using fly ash is the construction of a postensioned concrete beam of 12-ft long, 8-in deep, with a flange 12-in wide and 1-in thick, and a web of 3-in thick. The cementitious material consists of 75% cement and 25% fly ash type F, with a water/cement ratio (w/c) of 0.33. The strand is a 3/8-in cable installed with a parabolic shape. The beam test consists in the application of two central loads spaced 2'6". The first test produced the beam failure. A second project consisted in its repair with epoxy concrete following a test without failure. The students of other courses use this beam to perform additional experiments, such as Prestress Concrete, or Structural Dynamics. The results compare well with the theoretical calculations (Tito et al, 2006).

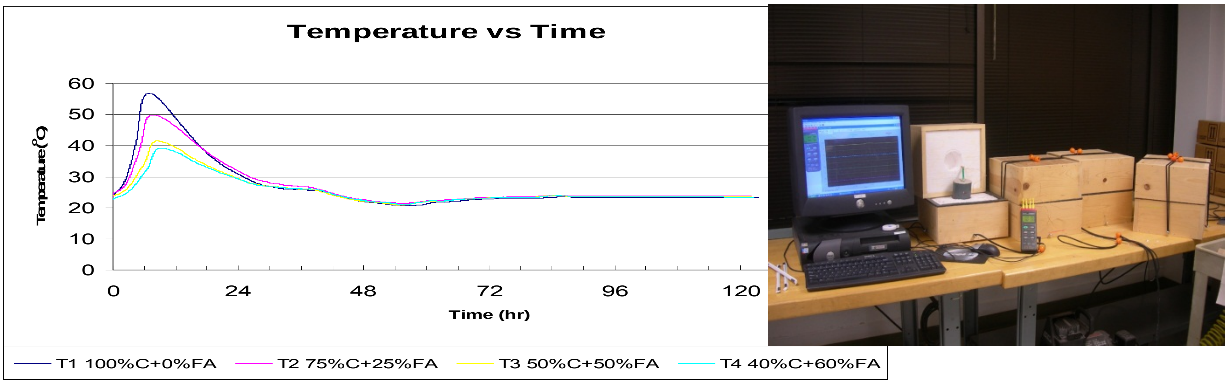


Figure 5: Temperature released during hydration process for different cement-fly ash ratios

PROJECTS WITH LIGHT WEIGHT AGGREGATES

The weight of concrete structures generally is as important as the live load; furthermore, for earthquake prone areas it becomes critical because the inertial forces due to the ground acceleration is proportional to the self-weight of the structure. Lightweight aggregates reduce the concrete weight in a range of 20% to 30% permitting smaller structural elements and less consumption of Portland cement. The total cost of the structure may be cheaper, inclusive considering the higher cost of the lightweight aggregates. In Houston, Texas, the cost in plant of the structural lightweight concretes may be $15 to $30 more expensive than the normal weight concretes; however, due the costs of labor and forming are similar, the total impact is in the range of 3% to 6% of the cost of a similar volume of poured concrete. A lightweight concrete may reach similar compression strength than a normal weight concrete.

The lightweight aggregates are from TXI Industries Inc. The material consists of expanded shale and clay (ES&C) manufactured by expanding minerals in a rotary kiln at temperatures over 1000 ^{o}C, conforming to the norm ASTM C330 that covers lightweight aggregates intended for use in structural concrete (TXI-ES&C, 2010). A representative of this industry served as a consultant for these projects, being one of his main recommendations to use the lightweight aggregates with water content (w) close to their absorption capacity. This practice avoids the loss of water needed for hydration and provides a reserve of water for internal curing.

Table 1 shows the properties of the aggregates; they were consistent during the different semesters used. The specific gravity depends on the grain size; the smaller grains are heavier than the long grains. Also, note that the absorption is relatively high and this has influence in the water requirements of the mix.

Table 1: Aggregate Properties from Laboratory Tests

Property	Light-weight Aggregates (ES&S)	
	Coarse	Fine
Unit Weight (M)	58 lb/ft^3	71 lb/ft^3
Average Specific Gravity (spg) (Smaller particles are heavier)	1.56	1.88
Absorption	15 to 20%	20 to 25%
Water Content (before mixing)	12 to 19 %	11 to 23%
Sieve Analysis:	Inside the recommended grading	
Maximum size	3/8-in	1/4-in
Coefficient of Uniformity, Cu	2.3	14.6
Coefficient of Curvature, Cc	1.4	2.4
Fineness modulus, FM	n/a	2.9

3.1 USE OF LIGHTWEIGHT CONCRETE FOR BEAMS

The experience with lightweight concrete consists of different applications and research projects. For the course Senior Concrete Design, the project was the construction of a segmental postensioned beam consisting of two massive end blocks and nine hollow segments, making a beam of 21'3" length. The lightweight concrete had a minimum strength (f'c) of 9 ksi and the segments were postensioned after positioning and alignment of all the segments. The lightweight concrete provided good workability of the fresh concrete, good finishing, and the segments were easy to handle. Figure 6 shows the test of the segmental beam (Tito et al, 2010).

Figure 6: Test of the postensioned segmental beam: a concentrated load at center.

Another project with lightweight aggregates is the construction and testing of two T-Beams. Figure 7 shows a schematic of this beam, which has 24'0" length, a depth of 20-in with 3-in wide web and a flange of 12-in and 1.5-in thick. The lightweight concrete has strength, f'c, of 8 ksi with a density of 124 pcf. The reinforcement consisted in a rebar #10 along the bottom of the web, and with stirrups consisting of a W5 wire spaced at 9-in. The beam is loaded with a jack positioned on top of a distribution beam, such that the beam receives two-point load spaced 4-ft and at center. The T-beam-1 failed prematurely with a jacking force of 16-kips because the distribution steel beam touched the flanges. For the T-beam-2, the load was applied only to the web reaching a maximum jacking load of 24-kips that match well with the theoretical predictions. Figure 7 also shows the crack pattern of the beam.

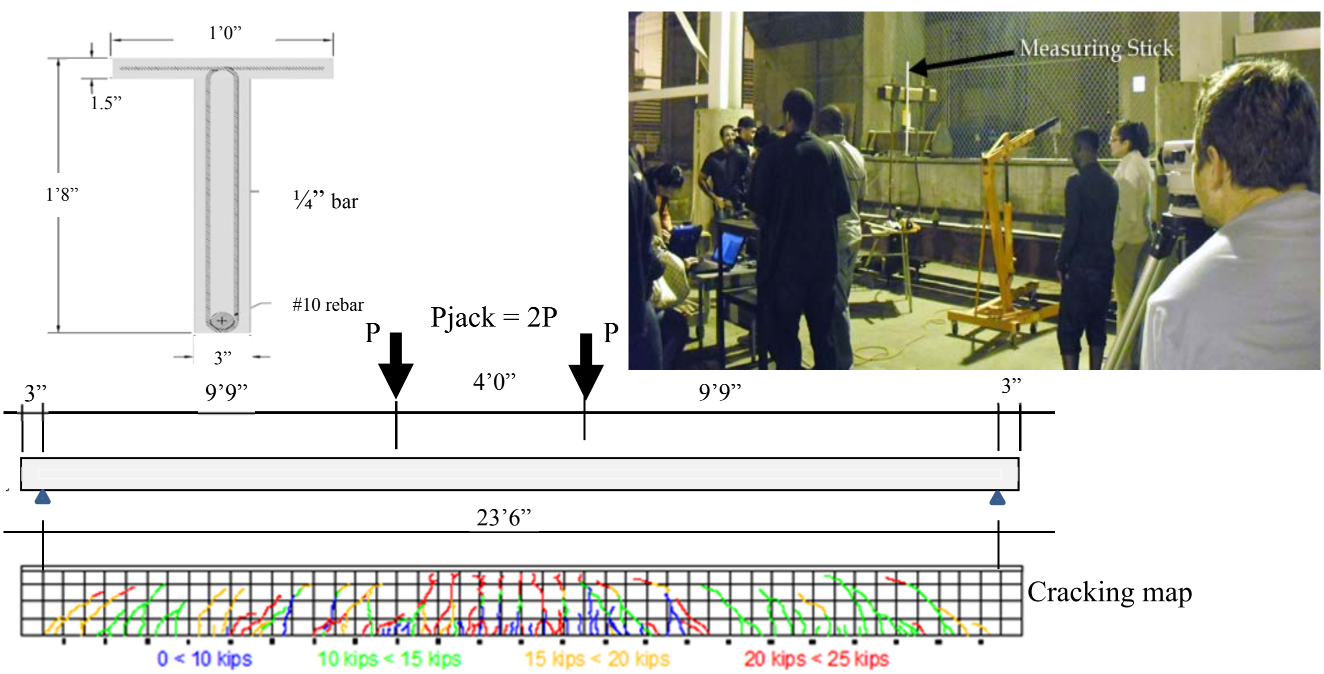


Figure 7: Test of the lightweight concrete T-beam

The T-beam-2 is loaded 2 times. Figure 8 shows the jacking force versus the deflection at center of the beams. The first loading applied a deformation of 3-in observing a ductile behavior after the yielding of the rebar. After one year the beam is re-loaded by a group of students of Reinforced Concrete Design, observing that the slope of the deflection follows the original unloading curve and reaches the yielding with the load of 24-kips.

Other experiments performed with these beams helped for the objectives of other courses of the program. As an example, in Structural Dynamics the students make experiments with the natural frequencies of the beams comparing successfully with the theoretical results.

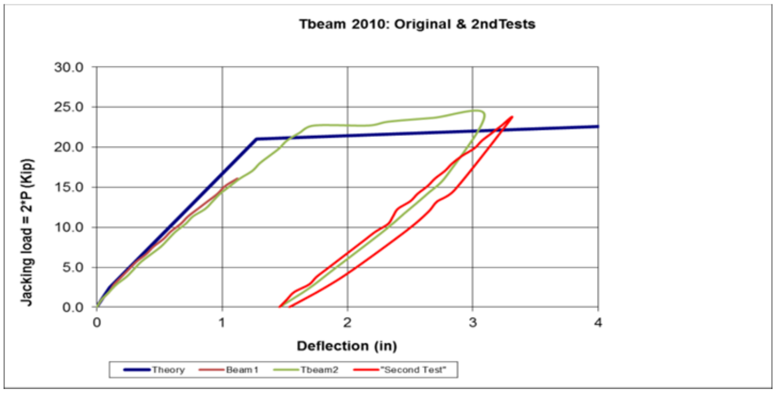


Figure 8: Jacking force vs. Deflection for the T-Beam

3.2 LIGHTWEIGHT CONCRETE PROPERTIES

The students of Modern Concrete Technology worked with different mixes of lightweight concrete to understand its engineering properties. The spreadsheet shown in Figure 1 is useful for the theoretical mix design. During the semester, the five groups of students prepared 10 mixes with 20 samples per batch, making about 1000 samples of lightweight concrete.

Table 2 shows the materials used for each batch, the water/cementitious (w/c) ratio, the density after form removal, and the average strength and its standard deviation. Although each group had the same mix design and the weights of the materials were controlled, the compression strength, f'c, varies until 35%, which highlights the importance of the mixing technique and labor.

Table 2: Materials used for each batch

MATERIAL	MIXES									
Mix number	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Water (lb)	6.63	7.37	7.39	7.11	8.05	3.50	2.52	3.75	3.08	4.70
Cement (lb)	16.77	19.63	15.71	18.71	14.11	11.56	8.61	12.69	8.41	17.31
Fly Ash Type F (lb)	0.00	0.00	3.93	0.00	0.00	0.00	0.00	0.00	0.00	5.77
Lightweight Gravel* (lb)	20.43	19.75	19.75	19.41	21.35	22.85	22.85	17.14	13.50	14.54
Lightweight Sand* (lb)	22.29	19.57	18.75	19.04	17.82	24.28	28.01	18.44	15.11	5.26
Super-Plasticizer (oz)	0.00	0.00	0.00	0.00	0.00	0.00	0.69	1.00	0.67	3.26
SureAir (oz)	0.00	0.00	0.00	0.86	0.65	0.53	0.39	0.43	0.38	0.00
w/c ratio	0.48	0.41	0.41	0.38	0.57	0.57	0.68	0.48	0.59	0.26
Density (pcf)	102	106	107	103	99	98	97	106	100	119
Strength f'c (ksi)	4.7+/-1.0	4.7+/-1.0	4.7+/-1.0	4.7+/-1.0	4.7+/-1.0	4.7+/-1.0	4.7+/-1.0	4.7+/-1.0	4.7+/-1.0	4.7+/-1.0
*The lightweight aggregates are saturated										

Figure 9 shows the compression strength of the mixes along the time. The curves have a wide range of f'c, varying from 2 ksi to 10 ksi. Figure 10 shows that heavier concretes are stronger, this is due the heavier concretes have more cementitious materials. Observe that concretes with f'c of 4 ksi to 6 ksi have a density between 102 to 105 pcf, which is about 25% to 30% lighter than normal weight concretes.

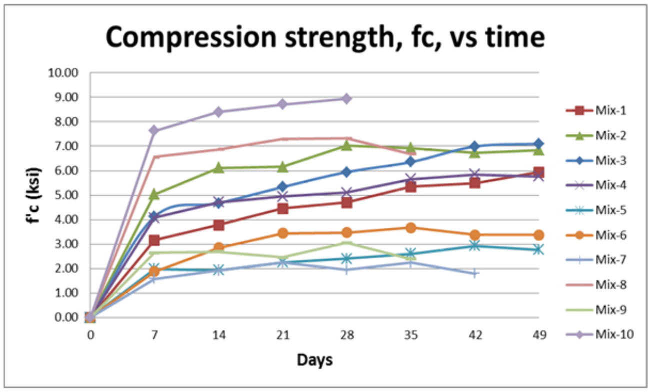


Figure 9: Compression strength (fc) vs time (days)

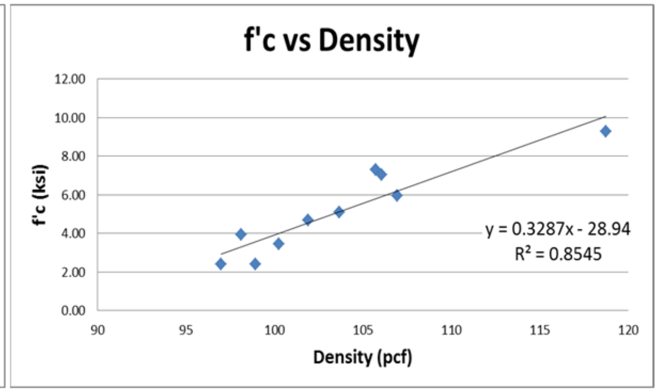


Figure 10: Compression strength at 28 days (f'c) vs density (pcf)

Figure 11 shows the variation of f'c respect to the water/cement ratio, w/c, appreciating that the strength is higher for lower w/c values. Figure 12 shows the relationship between the tension and the compression strength. The Brazilian Test is used to obtain the tension strength, as shown in Figure 4. The results show that the ratio of tension strength and the square root of the compression strength (ft/√(f'c)) has an average of 6.2, which is 24% greater than the value specified by the American Concrete Institute for lightweight concrete (ACI 318, 2011).

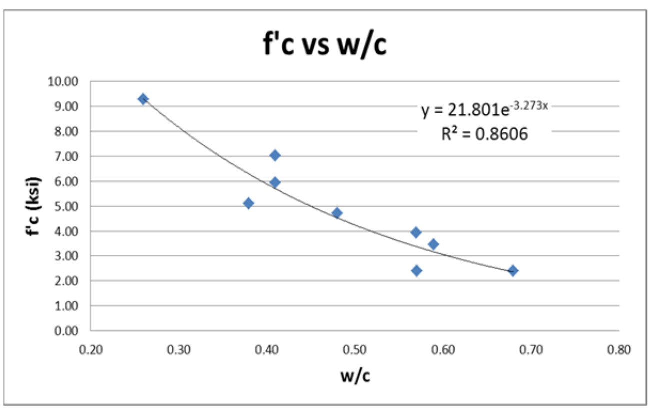


Figure 11: Compression strength at 28 days (f'c) vs water/cementitious ratio (w/c)

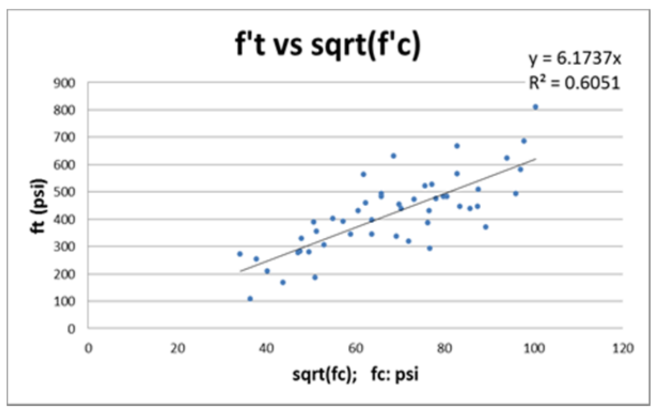


Figure 12: Tension strength vs. square root of compression strength, sqrt(f'c)

4. CONCLUSIONS

Through these years, the students of the Structural Analysis and Design program are exposed to the mix design, testing, and the use of Green Concretes for structural engineering uses. The projects permit the discussion of the engineering properties of the Green Concrete and the construction and testing of different type of beams whose behavior match well with the theoretical results. The students accept these hands-on projects with enthusiasm and motivation.

ACKNOWLEDGEMENT

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